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Validation of Objective Based Measures and Development of a Performance-Based Ranking Method for Load Carriage Systems

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Summary

Standardized objective measurements for the evaluation of load carriage include the development of a load carriage simulator, a stiffness tester, and a suspension system characteristics tester. In addition, human-based methods have been developed by which the performance of load carriage systems undergoing evaluation in standardized military activities can be assessed. The purpose of this paper is to summarize three studies that examine the correlation between these objective and human-based measures.

In the first study, face validation was undertaken by comparing the outcome of measurements made in pack-based systems using a simple biomechanical model. In the second study, a direct comparison of objective measures to human based measures in a cohort of military volunteers was undertaken. In a final study, a ranking method was explored as a way of characterizing military load carriage systems.

Study 1. Face Validation

Four steps were required in the development of a simple face validation for objective measurements. The first was the development of a static biomechanical model. In the second step, a number of conventional packs were analyzed and predictions made for the force distribution in the pack and the torso. In the third step, a comparison was made between model results and the discomfort observed in a cohort of military subjects. Finally, design limits for shoulder and lumbar forces in pack systems were established.

Biomechanical Model

A simple statistically determinant model was developed to predict the forces distributed to the torso (MacNeil, 1995; Pelot et al., 1998; Stevenson et al., 1995). It was based on the geometry of strapping and lean angle associated with each system. A typical configuration is show in Figure 1. The lean angle is shown at which the weight vector acts vertically (Figure 1a). Two strap forces are shown: the lower strap force (T1) and the upper strap force (T2) are directed to the shoulder. A third force, Fh, is the reaction force at the lumbar region. Note that there is no waist belt associated with this design.

In Figure 1b, the shoulder model is shown as a simple pulley with friction. The scalar difference between the strap forces, T1 and T2 is the frictional force Ff. The shoulder reaction force is the negative of the vector sum of T1 and T2 acting through the centre of circle representing the shoulder.

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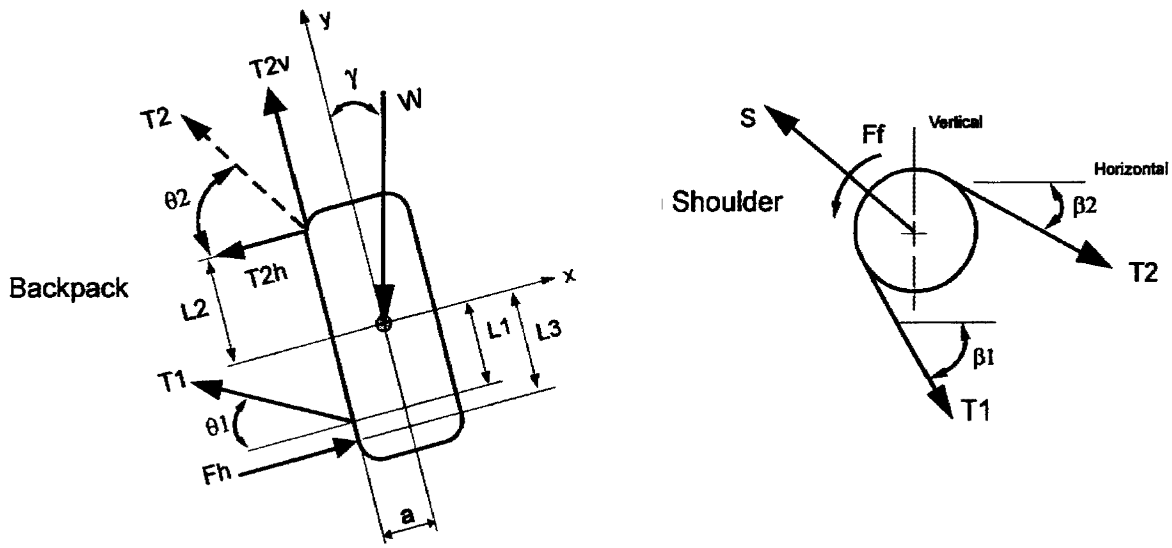


Figure 1. Biomechanical Model for Load Carriage. **(a)** Torso forces: T2 = upper strap, T1 = Lower strap, Fh = lumbar force, W = pack weight, γ = lean angle. **(b)** Shoulder forces: S = shoulder reaction force, Ff = friction force.

Table 1. Complete summary of biomechanical model results for the five test packs.

				Pack				
				A	B	C	D	E
Pack	Weight	(W)	Kg	32.1	33.1	32.7	31.8	31.8
	Inclination	(γ)	deg.	26.5	12.4	17.6	23.0	20.0
	COG offset	(a)	mm	122.9	133.1	116.7	105.8	127.1
Upper Strap	Horizontal Force	(T2h)	N	-3.0	89.7	41.2	8.4	39.0
	Vertical Force	(T2v)	N	137.9	182.3	218.4	201.9	209.9
	Location	(L2)	mm	192.9	51.2	325.9	187.6	238.0
Lower Strap	Angle	(θ1)	deg.	64.8	58.0	46.3	64.0	65.5
	Force	(T1)	N	160.0	159.0	120.8	94.4	91.0
	Location	(L1)	mm	350.5	271.7	-29.7	246.2	264.9
Lumbar Support	Force	(Fh)	N	206.1	243.7	221.7	171.5	183.3
	Location	(L3)	mm	287.3	248.3	89.2	227.1	206.8
Shoulder	Upper Strap Angle	(β2)	deg.	29.0	54.0	20.5	22.2	33.2
	Upper Strap Force	(T2)	N	138.0	203.2	222.3	202.0	213.5
	Lower Strap Angle	(β1)	deg.	37.3	45.2	29.0	41.1	45.5
	Lower Strap Force	(T1)	N	160.0	159.0	120.8	94.4	91.0
	Friction Force	(Ff)	N	-22.0	44.2	101.5	107.6	122.5
	Reaction Force	(S)	N	297.2	361.1	342.2	292.9	303.0
	Hor. Component	*(Sh)*	*N*	247.9	231.5	313.9	258.2	242.4
	Ver. Component	*(Sv)*	*N*	163.8	277.2	136.4	138.4	181.8
Load Distribution	Lumbar		%	29.1	16.1	20.9	22.0	20.0
	Shoulder		%	70.9	83.9	79.1	78.0	80.0
	Upper Strap	*(T2)*	*%*	39.5	48.9	61.0	58.0	59.0
	Lower Strap	*(T1)*	*%*	31.4	35.0	18.1	20.0	21.0

The input values for the model are the strap locations, the angle of the lower strap, the lean angle, the pack weight, and the shoulder angles. The output is the upper strap force and angle, the lumbar reaction force, and the shoulder reaction force. These result from a static balance of the forces and moments on the pack and on the shoulder.

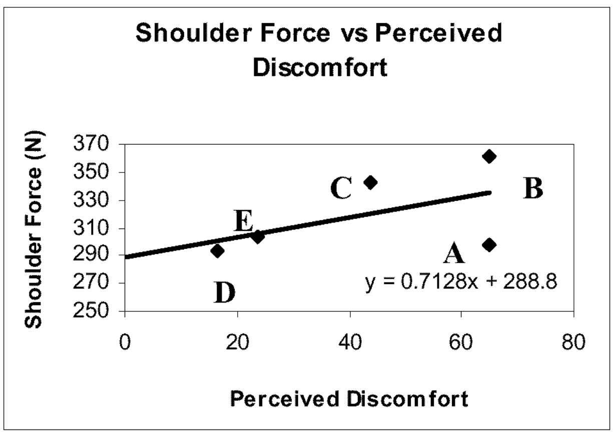
Five packs were evaluated geometrically using this model. All were loaded with 32kg consistently at a centre of gravity located in the midpoint of the pack. Three military and two commercial systems were evaluated. The measured geometric variables and resultant forces are shown in Table 1.

Comparison to Soldier Evaluations

Testing was undertaken with 20 soldier volunteers from a variety of military occupations (Stevenson et al., 1995). All consented to the study using standard human ethics consent procedures. Soldiers undertook a 6 km march wearing the test packs loaded with 32kg. At the end of the march, soldiers provided combined ratings for perceived discomfort in the shoulder and lumbar areas. Scores were converted to percentage of all users reporting significant pain.

The correlation between forces and discomfort is shown in Figure 2. The shoulder force showed a $r^2 = 0.56$ and lumbar force showed a $r^2 = 0.81$ with respect to perceived discomfort. Extrapolating these values to zero perceived discomfort indicated design limits for these parameters: a maximum lumbar force of 135 N and a maximum shoulder force of 145 N (for each shoulder).

It is interesting to note that while the pack weighs 32 kg, a total of 450 N applied body force was observed even in the lowest case (Pack D). In other words, 40% greater body force was experienced than the gravitational force on the pack itself! Of this, 160 N (50% of the gravitational force) was experienced as a lumbar force. This is a transverse shear to the spine and is only present because the shoulder strapping is at an angle to the torso.



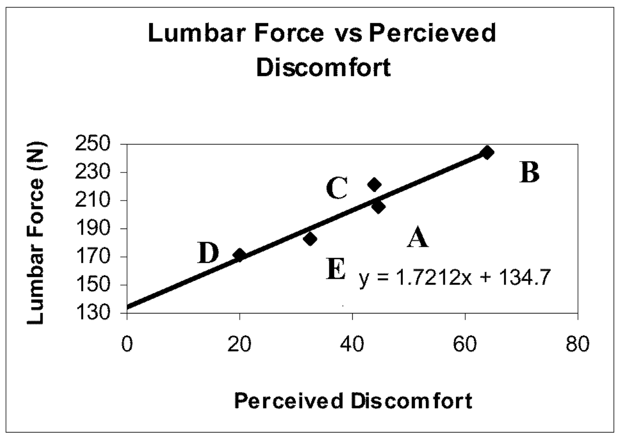


Figure 2. Body Forces versus Perceived Discomfort. (a) Shoulder forces (S in Figure 1 b). Total force is the sum of both shoulders. (b) Lumbar force (Fh in Figure 1 a).

Study 2. Construct Validity

A direct comparison between objective measures and subjective responses from soldiers was undertaken on nine military load carriage systems. Systems tested were from four countries and were evaluated in a variety of configurations that included rucksacks and webbing or load carriage vests.

Objective Tests

Objective tests undertaken were based on the load carriage (LC) simulator and the stiffness tester. In the load carriage simulator, a computer controlled torso is cycled in the vertical direction to simulate normal marching. Moments and forces at the hip are measured using a six-degree-of-freedom load cell. Displacement of the center of gravity of the pack with respect to the torso is measured using a Polhemus Inc. electromagnetic motion transducer (Fastrak™). Contact pressures at the anterior shoulder, posterior shoulder, upper lumbar and lower lumbar regions are measured using TekScan technology. This system is capable of measuring average contact pressures within 5% accuracy and peak pressures to 30% accuracy.

A second device was used to measure the stiffness of the pack system. The tester is capable of rotating the upper torso with respect to the lower torso in any of three directions while recording moment and angulation. Thus, torsional, lateral, and bending stiffness were obtained.

For each of the systems tested, the objective tests provided 39 measures of the mechanical characteristics of the system.

Human Performance Measures (FAST Trials)

Twenty-eight soldiers volunteered to undertake a series of activities (FAST[1] trials) testing mobility, function, agility, and comfort over a long march period (Bryant et al., 1997; Stevenson et al., 1997). Activities are indicated in the Table 2.

Table 2. Description of marching order testing activity stations (AS).

Activity Stations	Station Name	Description	Test Concept
1	Bent Balance Beam	- 10 m balance beam, 9 cm wide w/ 65 degree directional changes	Balance
	Boulder Hop	- 7 stones, 25 cm diameter w/90 degree directional changes	Balance
2	Straight Balance Beam	- 10 m balance beam, 9 cm wide	Balance
3	Fence Climb	- scale and descend 1.2 m fence	Agility
	Agility Run	- 10 pairs pylons (0.75 m apart) in slalom course over 10 m	Load Control
4	Side Slope Walk	- 7.5 m long w/ 26 degree side slope angle	Agility
	Forward Ramp Climb	- 4.5 m long w/ 21 degree angle of elevation	Load Control

At each station, soldiers were asked to rate acceptability in terms of balance, agility or load control on a scale of 1-6, 6 being acceptable. In addition, comfort was rated on a scale of 1-9, 9 indicating extreme discomfort. Tests were also undertaken to evaluate the ability to provide a range of motion for the hands and torso during the activities indicated in Table 3.

[1] FAST refers to First Assessment and Standardized Testing

Table 3. Description of marching order static tasks test.

Task	Task Name	Description
1	Hands above head	- reach both arms above head together - drop one arm, drop second arm, raise first arm, raise second arm
2	Hands in front	- reach both arms in front together - drop one arm, drop second arm, reach first arm, reach second arm
3	Forward flexion	- bend forward from waist, weapon in front - return to neutral, repeat
4	Lateral bending	- bend sideways at waist with weapon resting on floor - return to neutral, repeat to opposite side
5	Rotation	- rotate at waist with weapon in front - return to neutral, repeat to opposite side
6	Canteen access	- remove canteen from pouch in standing position - return canteen to pouch, repeat
7	Respirator Access	- remove gas mask from respirator pouch in standing position - return mask to pouch, repeat
8	Sit down	- move from standing to seated position
9	Lie in prone position	- move from seated to prone position
10	Emergency doff	- return to standing position - emergency doff pack with available quick release system

During the FAST trial circuit, soldiers marched a total of 6 km in one (1) km intervals. At the end of the circuit, ratings for discomfort and acceptability were also obtained for the march.

Twenty-eight subjects, all male, with an average age of 25.5 years, service duration of 5.4 years, height 1.78m and weight 82.1 kg, participated in the experiment. An incomplete block design provided a mean value of 12 assessments for each system. Each soldier only evaluated two systems and different soldiers in different pairings evaluated systems.

Statistical Analysis

A Pearson correlation table was developed for all measurements. A value of $r = 0.66$ indicated a correlation of $p < .05$ as shown in Table 4. LC-simulator measurements (including the stiffness measurements) are indicated to correlate significantly with FAST trial measurements by an asterisk. In several cases, correlations were found among single variables from the standardized measures and multiple human based measurements.

Table 4. Correlated load carriage and FAST trials measures.

Simulator Measures		Correlated Human Factors Measurements
Displacement (mm)	x *	Posterior Hip Discomfort
	y	
	z *	Posterior Hip Discomfort
	r *	Posterior Hip Discomfort
Moment (Avg, Nm/kg)	x	
	y *	Forward Flexion Mobility, Overall Comfort, Overall Fit
	z	
	r	
Force (Avg, N/kg)	x	
	y *	Front Mobility, Overhead Mobility, Posterior Shoulder Discomfort, March Thermal Comfort
	z *	Front Mobility, Overhead Mobility, March Thermal Comfort
	r	
Moment (Amp, Nm/kg)	x *	Torsional Mobility, Overall Mobility, Lie Function, Balance, Agility, Anterior Shoulder Discomfort, March Acceptability, March Comfort
	y	
	z *	Front Mobility
	r *	Posterior Neck Discomfort
Force (Amp, N/kg)	x	
	y	
	z *	Lie Function, Load Control, March Acceptability, March Integration, Overall Balance, Overall Comfort, Overall Fit, Overall Maneuverability
	r *	Load Control, March Integration
Shoulder Pressure (ANT)	Av (kPa)*	Posterior Hip Discomfort
	Pk (kPa) *	Doffing Function
	PDI *	Doffing Function
	F(N) *	Posterior Neck Discomfort
Shoulder Pressure POST	Av (kPa)	
	Pk(kPa) *	Doffing Function
	PDI	
	F(N)	
Lumbar Pressure UPPER	Av (kPa)	
	Pk (kPa)	
	PDI	
	F(N) *	Posterior Discomfort
Lumbar Pressure (LOW)	Av (kPa)	
	Pk (kPa)	
	PDI *	Front Mobility, Posterior Discomfort
	F(N)	
Stiffness (Nm/deg)	Torsion*	Overhead Mobility, Front Mobility
	Flexion*	Combined Function, Posterior Neck Discomfort, Low Back Discomfort
	Side *	Front Mobility, Anterior Shoulder Discomfort, Anterior Hip Discomfort

Shoulder Pressure Correlations

A correlation analysis was performed to determine a maximum allowable average pressure for the shoulder region. LC-simulator data for the anterior and posterior pressure sensors were combined and the average pressure in these regions provided the independent variable. Perceived discomfort rating reported by soldiers wearing the corresponding pack was the dependent variable.

Results showed that 95% of soldiers reported discomfort when the average shoulder pressure exceeded 20 kPa. Similarly, 90% reported discomfort at pressures exceeding 18 kPa. These values are greater than the 14 kPa, the physiological limit for blood flow occlusion.

Application to Load Carriage System Evaluation

In order to apply these findings to the evaluation of the acceptability of load carriage systems, it is necessary to compare soldier preferences to predictions of the standardized measures. Load carriage systems were selected for assessment based on their overall rating and performance in standard march. Ratings for two preferred systems (A and B) and two less preferred systems (C and D) are shown in Figure 3. A high score indicates a more preferred system.

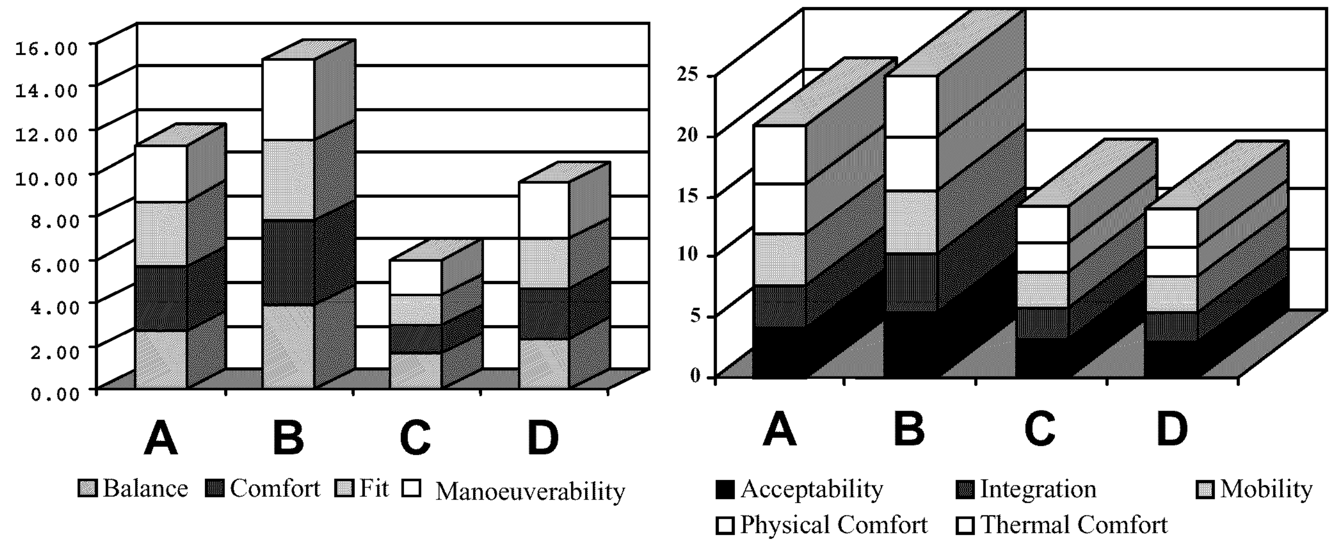


Figure 3. Overall Ratings for Four Systems. A and B were preferred systems, C and D were less preferred. (a) Overall ratings. (b) Extended march ratings.

Representative LC simulator results are shown in Figure 4. In Figure 4a, relative displacements for pack C in the forward direction exceed the 90th percentile for all packs measured in the study. Similar observations can be made for forward and vertical reaction moments and forces as shown in Figures 4b and 4c. This corresponds to the low overall ratings provided by the soldiers.

Observation of skin contact pressures in the shoulder region and back region are shown in Figure 5. Interestingly, all systems exceeded the 20 kPa discomfort rating in some region. Pack B, although highly rated, created high skin contact pressures both in the shoulder and in upper lumbar regions. However, soldiers apparently valued its ability in other areas, especially maneuverability, establishing a superior overall rating. Pack C, in contrast, indicated high discomfort ratings as well as poor ratings for maneuverability.

Figure 4a: LC Simulator – Relative Displacements (mm)

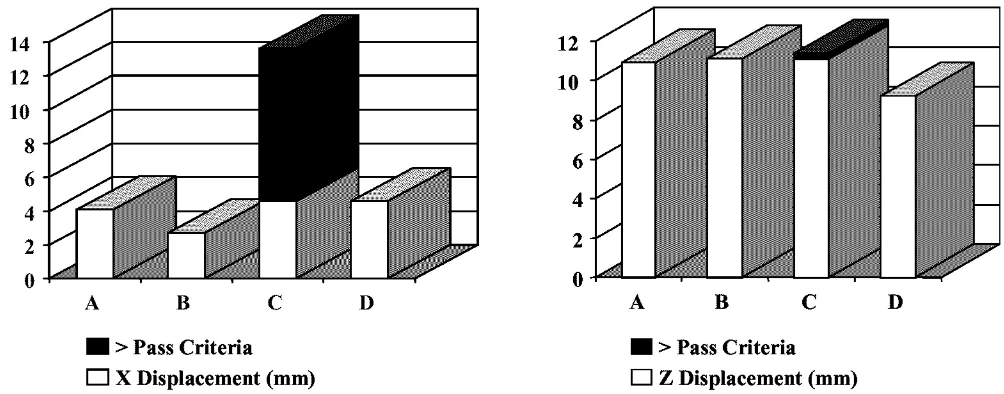


Figure 4b: LC Simulator – Reaction Moments (Nm/kg)

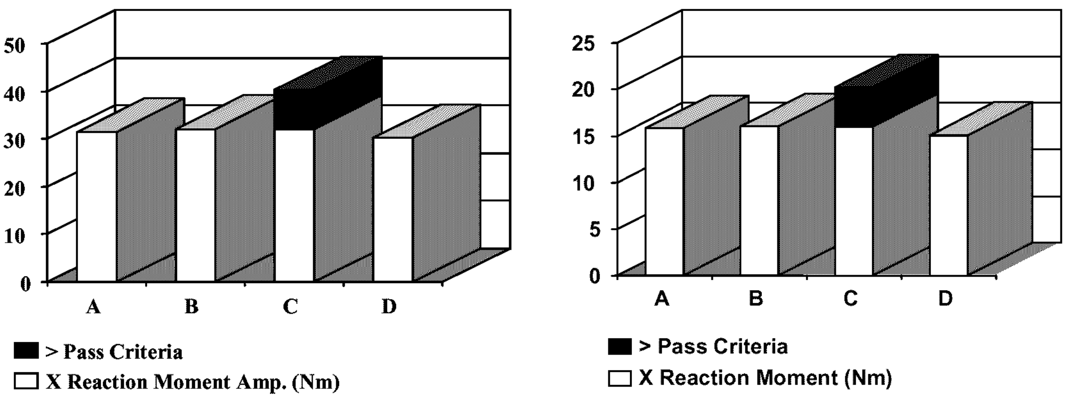


Figure 4c: LC Simulator – Reaction Forces (N/kg)

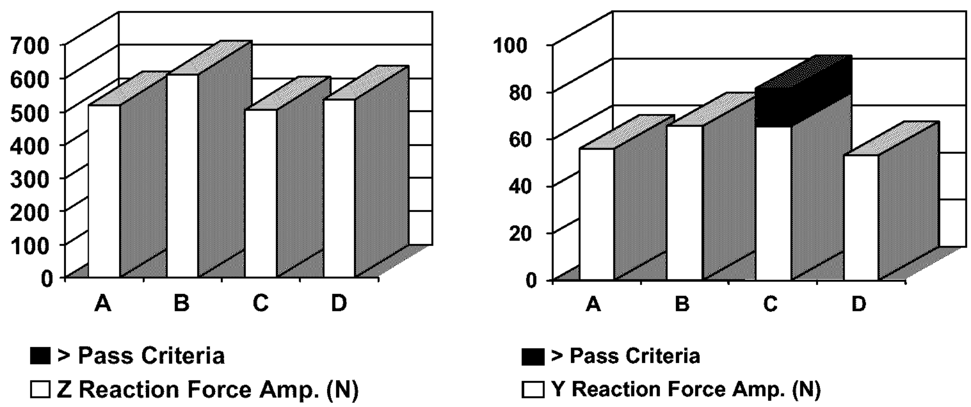


Figure 4. Relative Displacements, Moments and Forces for Four Systems. (a) Relative anteroposterior displacements (x) and vertical displacements (z) (mm). (b) Reaction moments about transverse axis (Nm). (c) Vertical reaction forces (z) and side reaction forces (y) (N). Pack C often fails the pass criteria.

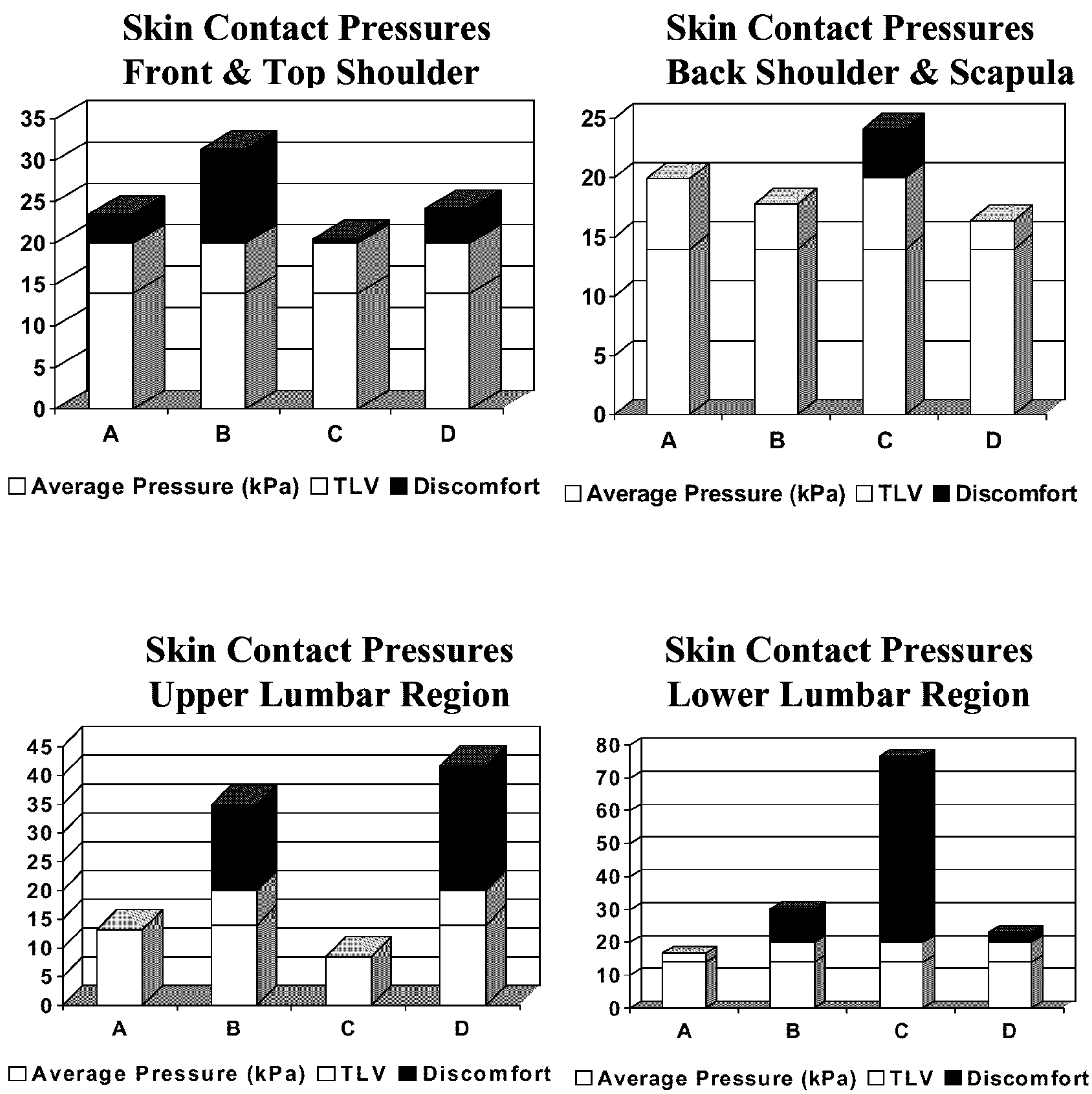


Figure 5. Contact Pressures for Shoulder and Back. Discomfort pressure = 20 kPa, TLV = 14 kPa. Average pressures shown for all cases. (a) Front and top shoulder. (b) Back shoulder and scapula. (c) Upper lumbar region. (d) Lower lumbar region.

Study 3. Performance-Based Ranking System

A third study was undertaken in which factor analysis was performed on all measured values of Study 2 (Doan, 1998). In particular, this study was undertaken to reconcile some of the tradeoffs associated with good performance in some measures and poor performance in others when establishing an overall rating for a load carriage system.

Factor Analysis

Factor analysis is a method by which the correlation among all measured variables are used to group highly correlated variables together into so-called factors. These factors are then manipulated as new variables that have a low correlation with each other.

From Study 2, 76 variables from the LC-simulator and FAST trials were produced for each load carriage system. These were reduced to 3 factors that accounted for a total of 71.1% of the variance in the measurements as indicated in Table 5.

Table 5. Results of the factor analysis on the total data set.

FACTOR	NOMENCLATURE	VARIABLES	VARIANCE
I	Balance	**Trunk/Body Motions** (Lateral bending, Torsional Rotation, Lie Down) **Load Transfer** (Posterior Shoulder Discomfort, Overall Comfort, General Load Control, Vertical Force Amplitude)	27.4 %
II	Load Control	**LCS Kinematics** (A.P Displacement, Transverse Displacement) **LCS Kinetics** (A/P Force Average & Amplitude, Transverse Moment Amplitude, Lower Lumbar contact Force)	23.4 %
III	Shoulder and Arm Restriction	**Reach Measures** (Hands above Head, Hands in Front) **Shoulder Restriction** (Vertical Force Average, Torsional Stiffness, Thermal Comfort)	20.3 %
Total			**71.1 %**

Factor 1 described the balance and general ability to move with the pack in place. Variables included lateral bending, torsional rotation, and lying down activities, as well as measures for posterior shoulder discomfort, overall comfort, general load control, and the vertical force amplitude.

The second factor was associated with physical variables involved with load control. These included A/P displacement, transverse displacement and corresponding amplitudes for forces and moments. In addition the lower lumbar contact force loaded on this factor.

The final factor combined both human and LC-simulator measurements in features associated with shoulder and arm motion. Variables included hands above the head and in front activities, as well as the average vertical force, torsional stiffness, and overall thermal comfort.

Expert Ratings

In order to compare these factors to overall ratings, three independent military load carriage system experts were surveyed. The experts rated the systems on a 3-point scale as unacceptable, acceptable or good. These ratings were combined into Friedman ANOVA estimate of inter-correlation between judges.

Total factor scores were based on the combined measurements of the variables associated with each factor. A factor score of zero is exactly at the mean for that factor. A score of –2, for example, is two standard deviations below the mean score for that factor.

The overall rating between the judges and the total factor scores is shown in Figure 7. For factor scores plus and minus 1.5, there was no consensus among ratings indicating that other criteria were used by experts in ranking. However, for scores outside this limit, the factor scores were consistent with those of the judges. The poorest rated system had a factor score of –1.84, while the highest rated system had a factor score of 3.06. This indicates similarity between the opinions of expert observers and the measures made in LC-simulator and human trials.

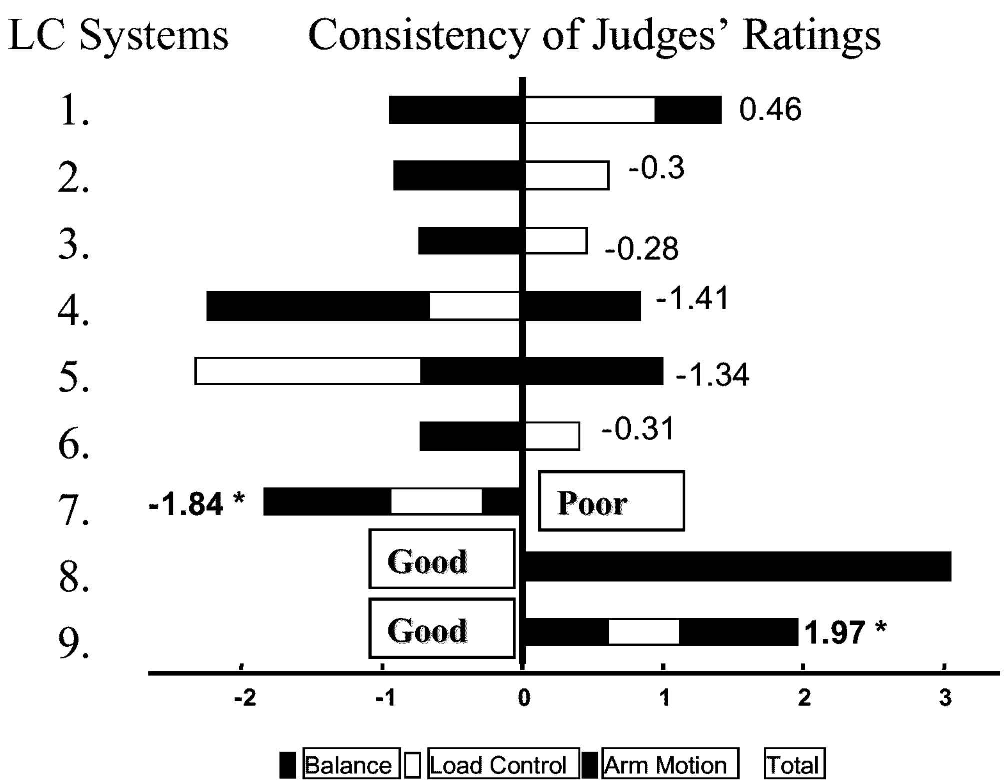


Figure 7. Load Carriage System Ratings. Total factor scores are indicated by number for each of the nine systems evaluated. The three lower systems were all rated as Poor or Good consistently by all experts. These also had the lowest and highest factor scores respectively.

Conclusions

Based on the results of the validation studies, the following conclusions are warranted:

- The face validity of standardized measurements for load carriage systems has been demonstrated using a simple biomechanical model. Results indicate a force limit of 145 N per shoulder and a lumbar force limit of 135 N for extended march conditions under heavy (32 kg) loads.

- There is a significant correlation of standardized measures and human measures as reported by soldiers undergoing simulated military activities. These measurements can be used to establish performance benchmarks for load carriage systems undergoing standardized testing.

- Average shoulder contact pressures of 20 kPa result in reported discomfort by 95% of soldiers undergoing extended march under heavy (24 kg) loads.

- Factor scores indicate that three factors can explain 71% of the variance in standardized tests. These scores indicate distinctly good or distinctly poor performance. However, rankings do not agree with expert observer rankings for near-average performance.

- A two-tier ranking system is indicated. In the first, standardized measures should be used to screen in or screen out particular designs. In the second stage, operational definitions and specific soldier preferences should be used to make selection based on performance requirements rather than physical attributes of the system.

Recommendations

The validation of the objective measures was completed in stages and with a limited number of load carriage systems to evaluate. It would be wise to repeat this study with a larger sample of systems both for face validity, construct validity and to develop a ranking system. It is anticipated that a confirmatory sample would help delineate the necessary features of a superior load carriage system for military applications. However, it will be necessary to complete human trials to gather the necessary subjective information on features and functions of the system in order to complete the rating system based on all of the aspects needed to determine a superior load carriage system.

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References

Bryant JT, Stevenson, JM, Reid SA, Doan JEB, Rigby, A. (1997). Research and development of an Advanced Personal Load Carriage System, Phases II and III. Section D: Development of acceptable criteria for physical tests of load carriage systems. *DCIEM Contract Report*, submitted in partial fulfillment of PWGSC Contract No. W7711-5-7273/001/TOS. 27 pgs. Report for DCIEM by Queen's University, Kingston, Ontario.

Doan, J.E.B. (1998) *Development of a Performance-Based Ranking Method for Load Carriage Systems,* M.Sc. thesis, School of Physical and Health Education, Queen's University, Kingston, Ontario.

MacNeil,S.K. (1995). *Validation and Development of a Mathematical Model of the Shoulder for Load Carriage,* M.Sc. thesis, School of Physical and Health Education, Queen's University, Kingston, Ontario.

Pelot, R.P., Rigby, A., Bryant, J.T., Stevenson, J.M. (1998). Research and Development of an Advanced Personal Load Carriage System*, DCIEM Contractor Report* No. CR 2000-092 (in press), submitted in partial fulfillment of PWGSC Contract # W7711-7-7420A. Report for DCIEM by Queen's University, Kingston, Ontario.

Stevenson JM, Bryant JT, dePencier RD, Pelot RP, Reid JG. (1995). Research and development of an advanced personal load carriage system – Phase I Section D – Development of Acceptable Criteria for Physical tests of Load Carriage Systems. *DCIEM Contract Report* (unpublished), submitted in partial fulfillment of PWGSC contract No. W7711-S-7356*,* 50 pgs. Report for DCIEM by Queen's University, Kingston, Ontario.

Stevenson JM, Bryant, J.T., Reid, S.A., Doan, J.B. DePencier, R., Saunders, G., & Siu, D. (1997). Design and validation of measurement systems for load carriage. *Advances in Occupational Ergonomics and Safety,* (edited Das and Karwoski) IOS Press Inc., Virginia, pp.189-192.